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An optimization approach for components built by fused deposition modeling with parametric internal structures

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Abstract

Additive manufacturing processes are employed to create physical models from three-dimensional (3D) computer-aided design (CAD) math data. A solid model or water-tight surface model is used as the input, which is sliced into layers, and travel paths are created for each layer. The object is built by layer by layer stacking, with supporting structures for overhanging geometry and undercuts being created where necessary (process dependent). Fused deposition modeling (FDM) is an additive fabrication process that builds a part from extruded filaments of a melted thermoplastic. Several studies have focused on the depositing parameters; however, none of them have characterized internal support structures in different geometrical arrangements. The incorporation of reconfigurable parametric internal matrix structures based on primitive elements will balance the mechanical properties, the material usage and the build time. Parametric internal structures are designed, and compressive test components built and tested both experimentally and using simulation tools to depict the compressive characteristics. Extensive physical testing is done as the components built by the FDM process have anisotropic properties. The material usage, build time, and loading characteristics are captured for a variety of parametric structures (solid, shell, orthogonal, hexagonal, pyramid) build orientations, and internal densities (loose, compact). From this data, a model is developed that serves as a predictive tool to: (i) estimate the mechanical properties and (ii) calculate the build time and materials utilized based on various internal structural configurations for the component's application. A model that generates an optimal solution (minimum material, minimum build time, etc.) needs to be developed. Using the collected data as a foundation, an optimization model that considers the build time, material usage, surface finish, interior geometry, strength characteristics, and related parameters is presented and can be used to assist designers making informed decision with respect to strength, material usage and time, etc. is developed using the Genetic Algorithm approach.

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1. Introduction

Additive manufacturing processes are employed to create physical models from three-dimensional (3D) computer-aided design (CAD) models. Fused deposition modeling (FDM) is an additive fabrication process that builds a product from thin layers of extruded filaments of a semi-melted thermoplastic. The part's mechanical properties depend mainly on variable factors such as the material's depositing orientation, the filament's flow rate, the rasters' separation, and the extrusion temperatures. These parameters control the part's meso-structure (when the extruded fibers' scale approximate to 0.1 mm) characteristics and influence the fiber-to-fiber bonding. The dependence of the FDM material's properties to the listed manufacturing parameters provides the designer the ability to optimize the mechanical performance while modifying the part's meso and macro structures.

The two main FDM manufacturing strategies (solid and shell) may be used indistinctively; however, there are applications where the solid build strategy may not be necessary and even problematic. When there is a thick wall – thin wall blend, this configuration may lead to distortion [1].

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It is known that distortion can occur in a casting process where there are thick wall-thin wall junctions, and preliminary research has shown that when thick and thin wall conditions exist in a part to be built by the FDM process, this can impact its deformation. However, a shell building strategy may not be desirable since poor stiffness may lead to a prototype which is too weak for the application.

Evidently, the mechanical characteristics of internal support material have not been fully studied and defined yet. Hence, it is desirable to include internal supporting structures with known properties and behavior that will provide the support needed while balancing the amount of material used (both model and support). At the same time, it is important to characterize the material's meso-structure and the mechanical properties in a macro scale as a function of the built parameters which include, among others, the topology of the deposited layers of the part (the internal supporting structure arrangement or cross-sectional morphology), the raster orientation, and the part orientation, which is the goal of this research.

2. Literature Review

2.1. Mechanical characterization of FDM materials

There are many ways to approach the mechanical characterization of the FDM products. Research has shown that one way for defining the properties of the type of materials used in this process is by traditional mechanics of materials, which express the average macroscopic stress and strain states in terms of constituent stress-strain states using displacement continuity and force equilibrium conditions. Basic assumptions in modeling unidirectional composites include: homogeneous (isotropic linear elastic constituent behavior) and homogeneous (orthotropic or transversely isotropic linear elastic composite behavior) [2].

The internal structure of FDM parts is analogous to the fiber layout in composite materials. As such, various researchers have attempted a number of methods to characterize this condition. El-Gizawy et al. [3] discloses that classical lamination theory (CLT) has been used to predict the failure criteria of FDM parts. Another approach described by Rodriguez et al. [4] includes the definition of a representative volume element, which is statically representative of the infinitesimal material neighborhood of that material point.

The mechanical properties of the FDM's acrylonitrile butadiene styrene (ABS) thermoplastic are characterized experimentally according to the scope and characteristics of the specific research being performed. In view of the scope and purpose of this research, CAD models with internal web-like structures should be representative of the macro-mechanical properties from the results obtained from test samples under standard test conditions. In this sense, it is believed that the meso-structure arrangement affects the mechanical properties of the FDM ABS material. That is to say, the mechanical strength is influenced by the part orientation - anisotropy of the monofilament deposition.

Similarly, the fiber-to-fiber bonding (the bonding density) affects the strength and the material degradation since the air gap controls the quality of the material at high stress values.

2.2. FDM process characterization

There have been significant experimental studies to comprehend the effect of the FDM parameters in terms of the modeled part characteristics such as surface finish, accuracy (distortion), and material reduction. Process parameters (also named as manufacturing parameters) of FDM may affect the localized material properties, namely: the density, porosity, surface finish, and specific mechanical properties. According to Agarwala et al. [5], the manufacturing parameters that affect the FDM prototyped parts may be divided into four categories. These parameters are operation specific, machine specific, materials specific, and geometry specific.

The operative parameters are modifiable providing extended flexibility in the light of fabricating high quality FDM processed parts. Regardless of the complete optimization of existing FDM processes, day-to-day practice has shown that defects can result when using the FDM process to manufacture parts. This is caused by the nature of the process itself. As there are heat gradients due to melting, solidification, airflow, slicing, orientation and form of the component being built, each processed part is unique. The process parameters for the FDM rapid prototyping (RP) process number more than a dozen. However, not all of the parameters influence the strength characteristics. Table 1 summarizes the relevant parameters evaluated by researchers. Researchers have focused on optimization of the surface finish, dimensional accuracy, or the strength.

Table 1. Summary of FDM manufacturing parameters research [2].

Researcher	Air Gap	Road Width	Envelope Temperature	ABS Color	Raster Angle Orientation	Contour Fill	Extrusion Temperature	Layer Thickness	Deposition Speed	Build Plane
Agarwala et al. [5]		✓	✓			✓	✓			
Ahn et al. [6]	✓	✓		✓	✓		✓			
Anitha et al. [7]		✓						✓	✓	
Bakar et al. [8]					✓	✓		✓		
Bertoldi et al. [9]					✓					✓
Es-Said et al. [10]					✓					
Fodran et al. [11]	✓	✓						✓		
Lee et al. [12]	✓	✓			✓			✓		
Montero et al. [13]	✓	✓		✓	✓		✓			
Rodriguez et al. [14]	✓	✓	✓		✓		✓			✓
Sood et al. [15]	✓	✓			✓			✓		✓
Too et al. [16]	✓	✓						✓		

Parameter optimization of the number of levels and their ability to manipulate such in order to obtain inclusive results has been studied. In this sense, degrees of freedom (DOF) are defined as the number of comparisons between process parameters that need to be made to determine which level is better, and specifically, how much better it is. Again, the parameters selected depend on the objective of the research in terms of the optimization of the FDM properties including accuracy, surface finish, material optimization, and strength optimization.

2.3. A multidisciplinary approach

Table 2 depicts a chart where similar approaches from a wide variety of studies have shown meaningful development in the understanding of rapid prototype (RP) optimization. Specifically, this includes parts with optimized load-supporting characteristics that demanded preparing models that reflect strength and stiffness in the RP material in relation to meso and macro-structural parameters. In this sense, the design for optimization approach encompasses works in the computer aided design (CAD) domain. These studies are related to optimization of the math algorithms and other mathematical operations embedded in a variety of software applications or CAD modeling instructions developed to perform as desired. It is important to mention that, unlike such methods and mathematical techniques, the present approach is semi-empiric. However, this does not downgrade the merit of the novel approach herein followed. For this reason, a different method is to be followed in order to give a meaning to the characterization of the FDM ABS parts. Evidently, a suitable method to correlate the experimental results obtained from the physical experimentation with the virtual simulation is to be chosen, such as the one described by El-Gizawy et al. [3] where finite element analysis (FEA) is described as the optimal tool.

Table 2. Summary of advanced FDM optimization research [2].

Researcher	CAD Algorithms and Computational Methods	Optimization of the Mechanical Performance	Optimization of the Building Parameters	Modification of the Internal Topography of the Part	Characterization of specific FDM Parts	FEA and/or Experimental Testing
Persson et al. [17]		✓			✓	✓
Arriaga et al. [18]		✓				✓
Es-Said et al. [10]		✓	✓		✓	✓
Fodran et al. [11]		✓	✓		✓	✓
Pande et al. [19]	✓					
Rodriguez et al. [14]		✓	✓		✓	✓
Lam et al. [20]	✓		✓	✓	✓	
Yao et al. [21]	✓	✓		✓	✓	✓
McMains et al. [22]	✓		✓		✓	
Galantucci et al. [23]		✓	✓	✓		✓
Park [24]	✓			✓		

3. Methodology

3.1. Parametric modeling

The CAD modeling involves a systematic approach that is carried out in commercial CAD modeling software. Primitive elements are joined in a pattern to construct complex web-like structures. These arrangements are parametric assemblies of truss structures which are capable of being modified by the designer. Once the elements are created, they are inserted into a solid element, which has been modified to a shell structure.

The logic employed to create a part **P** with internal structures is partially described in Fig. 1. A primitive modifiable element (a) is utilized to form structures by joining the spherical ends along with specific geometrical constraints to create complex truss-like structures, as shown in Fig. 1 (b). The internal structure can have orthogonal, hexagonal, or pyramidal truss structures. Independently, the solid component is shelled. Finally, a part with internally modifiable truss-like arrangement is obtained by eliminating the truss components outside the shelled part bounding walls and joining this new interior structure to the shelled part. This final part configuration is shown Fig. 1 (c).

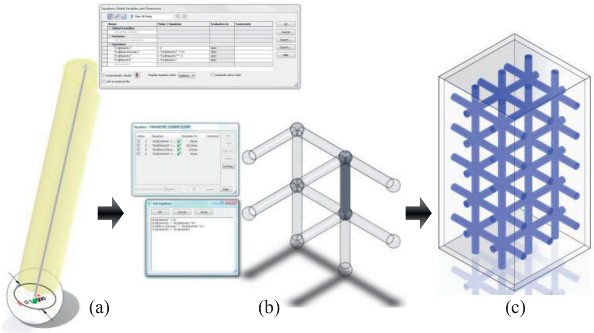


Fig. 1. Parametric modeling of the modifiable element structure (a), the parametric web-like structure, and (c) the internally modified shelled part [2].

Therefore, $\mathbf{P} = \Delta\ (M, r) \cup (S \cap M)$,

where $\cap$ and $\cup$ are intersection and union respectively, $\Delta\,(M, r)$ is the shelling operation of model **M** by a distance r, and $(S \cap M)$ is the Boolean operation of the intersection of the parametric internal structure **S** and the model **M**.

Specimens with various internal structure configurations are designed, built (using various build orientations), and tested. They are also simulated in a virtual environment. The results for both the physical and virtual tests are analyzed and compared. Fig. 2 depicts the methodology followed.

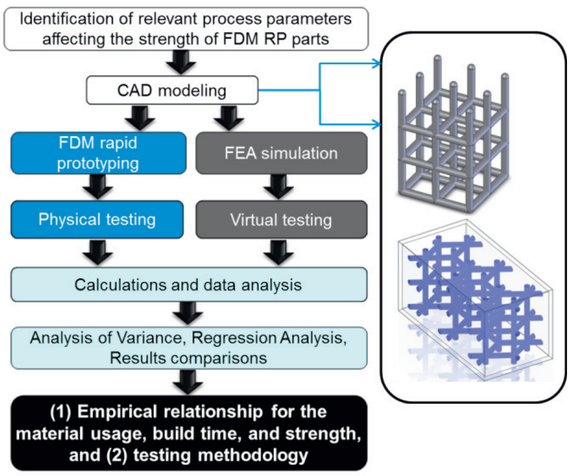


Fig. 2. Experimental and virtual simulation methodology for the performance characterization of internal support structures [2].

3.2. Part orientation optimization using genetic algorithm

The introduction of parametric internal structures within component introduces another level of complexity associated with determining optimal process parameters. To address this challenge, the Genetic Algorithm (GA) module in Matlab's global optimization toolbox is used to optimize the part orientation. The Genetic Algorithm (GA) is a stochastic search method for solving, both, constrained and unconstrained optimization problems that is based on a natural selection process that mimics biological evolution [25]. It explores the solution space by using concepts taken from natural genetics [26] and evolution theory [27].

The GA starts with an initial set of solutions which is known as a population. The individuals of the population are called chromosomes which are evaluated according to a predefined fitness function, in this case the total cost. Each chromosome includes several genes. The gene represents normalized evaluation criteria which are specify weights for build height, staircase error factors, material utilization factor, surface area in contact with support structures and volume of support structures [28]. The chromosomes evolve through successive iterations called generations [26]. A new generation is created by changing chromosomes in the existing population through crossover and mutation [29]. In the present work, a single-point crossover is used and the probability of crossover should be more than 0.75 and probability of mutation should be 0.1 [28]. The other input parameters which are used for the GA are the population size of 40, generation size of 50, a crossover rate of 90% and a mutation rate of 10% [28]. The fitness function that is used in genetic algorithm for the model is a weighted average of the five normalized evaluation criteria [28]. Table 3 comprises the notations and their description used in the fitness function.

Table 3. Nomenclature of the fitness function (F) formula components [28].

Notations	Description
W_1	Build Height
W_2	Staircase error factor
W_3	Material utilization factor
W_4	Part surface area in contact with support structures
W_5	Volume of support structures based on their relevance to the RP process
H	Actual build height
Ra_avg	Staircase error factor
PM	Material utilization factor for the hollowed RP part
A	Surface area in contact with supports
V	Volume of Supports
Z_{max} - Z_{min}	The actual oriented part build height along Z axis
Ra_i	Roughness (µm)
A_i	Area of the *i*th triangular facet of STL file
θ	Angle between facet normal and Z-axis

Hence, the fitness function (F) is,

$$MinF=1+(W_1*H)+(W_2*Ra\text{-}avg)+(W_3*PM)+(W_4*A)+(W_5*V) \qquad (1)$$

Where

$$\sum_{i=1}^{5} W_i = 1 \qquad (2)$$

$$H=\frac{Z_{max}\text{-}Z_{min}}{1.2*diagonal\_of\_bounding\_box} \qquad (3)$$

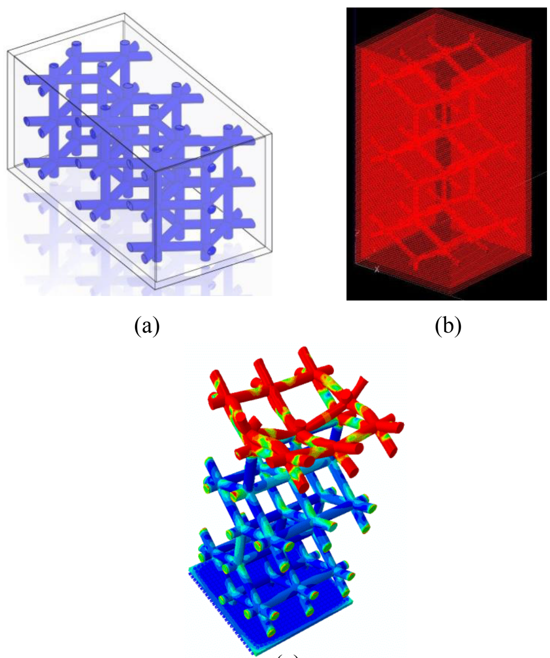
$$Ra\_avg=\frac{\Sigma Ra_i A_i}{\Sigma A_i} \qquad (4)$$

$$Ra_i=\frac{slice\_thickness*70.82}{\cos\theta} \qquad (5)$$

4. Case Study

4.1. Physical and experimental approach for assessing compressive load behaviors

A set of 32 different compression specimens are replicated three times, and built using a Fortus 400 MC with ABS material. The experiment set and number of samples are extensive. The goal of this research is to obtain an accurate estimation of general behavior for all the different parameters subject to study in the present research. Fig. 3 depicts the CAD model with one of the arrangement sets studied in this research, where (a) is a compression specimen with an internal orthogonal of thin truss-like solid elements, (b) is the graphic representation of the hexagonal arrangement specimen sliced in layers by the RP software, and (c) is the result of the FEA simulation (compressive test) of the same hexagonal arrangement specimen in a computer aided engineering (CAE) software.



(a) (b) (c)

Fig. 3. Schematics of (a) SolidWorks® CAD 3D model, a (b) Insight® sliced representation, and an (c) Abaqus/CAE® finite element simulation [2].

Table 4 presents the results from the RP software simulations for various experimental configurations including model material, support material, building time and maximum load before deformation.

Table 4. Differences between the RP compression specimens built by FDM based on different orientation, internal density, and raster angle [2].

Type of Structure	Raster Angle	Build Plane	Internal Density	Model Material (cm^3)	Support Material (cm^3)	Time (min)	Maximum Load (N)
Orthogonal	-45°/ 45°	XY	Loose	1.98	3.06	24.66	1734
Orthogonal	0°/ 90°	XY	Loose	2.11	3.08	24.66	1943
Hexagonal	-45°/ 45°	XY	Loose	2.06	2.92	20	1846
Hexagonal	0°/ 90°	XY	Loose	2.05	2.903	20.33	1917
Pyramid	-45°/ 45°	XY	Loose	2.03	2.91	24.66	1442
Pyramid	0°/ 90°	XY	Loose	2.01	2.91	24.66	1364
Solid	-45°/ 45°	XY	-	5.88	0.38	9.33	19100
Solid	0°/ 90°	XY	-	5.78	0.38	8.66	19288
Hollow	-45°/ 45°	XY	-	2.003	2.53	16.33	1416
Hollow	0°/ 90°	XY	-	1.99	2.56	16	1151

4.2. FEA virtual simulation

The comparison between the various physical experiments and the corresponding FEA analysis for five distinct internal structure configurations is presented in Fig. 4. Values from the FEA simulation were picked as the deformation approached the rupture value of the experimental specimens for each of the arrangement sets. Similarly, the FEA simulation values were selected as the deformation approached the maximum allowable value from the universal testing machine for each of the internal arrangement sets.

Three physical experimental replications were performed. It was determined that the range values of the physical experiments fail within the values of the FEA simulation (the average experimental range for the fail point is less than 120N). This result indicates that for compression tests, the FEA simulation is accurate and truly represents the behavior exhibited with the physical experiments. Therefore, it can be assumed that the FEA simulation will provide a reliable estimation of the compressive loads and respective deformation for parts with similar characteristics as the ones simulated in this CAE software.

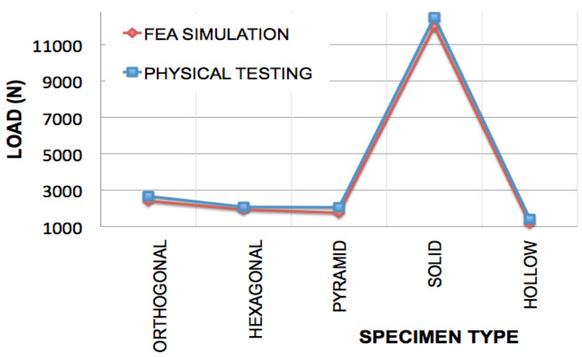


Fig. 4. Similarity between the FEA and the physical compressive test [2].

4.3. Genetic Algorithm

The optimization goal in this research is to determine the optimal build orientation (which balances the five factors listed in Table 3) for the specimen illustrated in Figure 3 (b), which has orthogonal internal structures. Representative build orientations for the component and their associated fitness functions are provided in Figure 5 and Table 5. In Table 5, the weight factors ($W_i, \forall i$), optimum orientation angles (θ_x, θ_y) and the fitness function (F) is presented for three of the 50 cases. The parameters associated with the A1 orientation in this case study generated the optimal answer with fitness function F=4.06 (the minimum value).

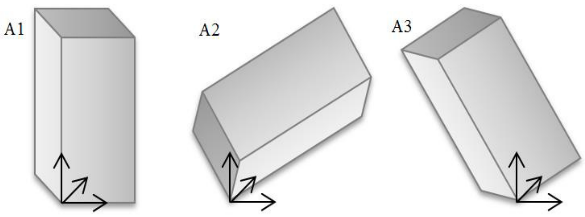


Fig. 5. Cases in Table 5 illustrating orientation variations.

Table 5. Part orientation and fitness function.

Cases	Weights					Optimum Orientation		Fitness Function
	W1	W2	W3	W4	W5	θ_x	θ_y	F
A1	0	0	0	0	1	90°	0°	**4.06**
A2	0.2	0.2	0.2	0.2	0.2	15°	45°	136.58
A3	0.15	0.2	0.15	0.2	0.3	120°	178°	133.71

Table 6 shows the detailed results for the optimal orientation (Fig. 5-A1) including the process performance parameters in terms of build height, staircase error and material utilization factor (PM). The result shows that by varying the weights (W_1, W_2, W_3, W_4 and W_5), optimum part orientation is exactly same as determined by the physical experiments.

Table 6. Selected parameters for case A1.

Notations	Description
Z_{max},- Z_{min}	25.4
Diagonal of bounding box	1.67
A	161.29
θ	0°
Slice thickness	6.53
PM	50.85
V	3.06
θ_x	90°
θ_y	0°
H	12.7
Ra	450
Ra_avg	450

5. Conclusions and Future Work

There may be build conditions where the two main FDM manufacturing strategies (solid and shell) are not desirable. Introducing internal structures to provide balance between material usage and strength can provide new opportunities. However, this adds complexity to the manufacturing strategy, and extensive physical testing to determine the mechanical behaviors is time consuming and expensive. Virtual experimentation addresses these concerns, and it is shown in this research that the FEA simulation well represents the physical experiments performed on the compressive samples. Regardless of the assumption of elastic behavior, the compressive specimens behaved as if no buckling was present. Thus, there is no need for deepening the study into the non-linear representation. Also, based on the data gathered from the results, there is no need for a large number of samples since load values remain within a relatively small range.

Moreover, the thermoplastic material exhibited a brittle behavior that can be approached as being located in the linear elastic region. Further study of composite materials and the interactions at the boundaries is to be performed and characterize to understand the effect of the internal topology of the samples. This leads to a further study that deals with heat deposition characterization, which is inherently related to distortion. Hence, it can be assumed that reliability of the material characterization is strictly dependent not only of the RP technology, but the model/year of the machine from the same type of technology.

Further to the characterization of the mechanical properties of the specific internal arrangement sets inside a part, the optimization of the build parameters is fundamental. Therefore, GA methods are developed to determine the optimal parameters that affect the mechanical meso and macro-structural properties, build time, material use, and surface finish. Future work will consist of case studies with more complex geometry and will address meeting minimum compressive and tensile load requirements.

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